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California earthquake history

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Abstract

This paper presents an overview of the advancement in our knowledge of California's earthquake history since ~ 1800, and especially during the last 30 years. We first review the basic statewide research on earthquake occurrences that was published from 1928 through 2002, to show how the current catalogs and their levels of completeness have evolved with time. Then we review some of the significant new results in specific regions of California, and some of what remains to be done. Since 1850, 167 potentially damaging earthquakes of $M \sim 6$ or larger have been identified in California and its border regions, indicating an average rate of 1.1 such events per year. Table I lists the earthquakes of $M \sim 6$ to 6.5 that were also destructive since 1812 in California and its border regions, indicating an average rate of one such event every ~ 5 years. Many of these occurred before 1932 when epicenters and magnitudes started to be determined routinely using seismographs in California. The number of these early earthquakes is probably incomplete in sparsely populated remote parts of California before ~ 1870. For example, 6 of the 7 pre-1873 events in table I are of $M \geq 7$, suggesting that other earthquakes of M 6.5 to 6.9 occurred but were not properly identified, or were not destructive. The epicenters and magnitudes (M) of the pre-instrumental earthquakes were determined from isoseismal maps that were based on the Modified Mercalli Intensity of shaking (MMI) at the communities that reported feeling the earthquakes. The epicenters were estimated to be in the regions of most intense shaking, and values of M were estimated from the extent of the areas shaken at various MMI levels. MMI VII or greater shaking is the threshold of damage to weak buildings. Certain areas in the regions of Los Angeles, San Francisco, and Eureka were each shaken repeatedly at MMI VII or greater at least six times since ~ 1812, as depicted by Toppozada and Branum (2002, fig. 19).

Key words *California – historical earthquakes*

1. Introduction

California's written history is very short. It started in 1769 with the diaries of the first Spanish explorers. That year they felt earthquakes in the vicinity of Los Angeles during their travel from San Diego northward. The Spanish priests established 21 Catholic missions near the coast, from San Diego in 1769 to San Francisco de Solano in 1823 (fig. 1). Many of the missions' annual reports are

available in the Santa Barbara Mission Archives. These reports documented the numbers of births, deaths, baptisms, livestock, agricultural harvest, and mentioned earthquakes when they damaged the buildings. The Missions were secularized in 1834, ending the annual reports and leading to general abandonment and disrepair.

For the next 15 years, until the 1849 Gold Rush and United States statehood, the sources of information were mostly the diaries of travelers and the records of ships' captains. In 1849 regular newspaper publishing started in San Francisco and in the gold country east of Sacramento. Felt earthquakes were noted in the newspapers, which continued to spread across California with time as the population increased. The descriptions of the earthquakes were cataloged by various contemporary researchers, and were later interpreted in terms

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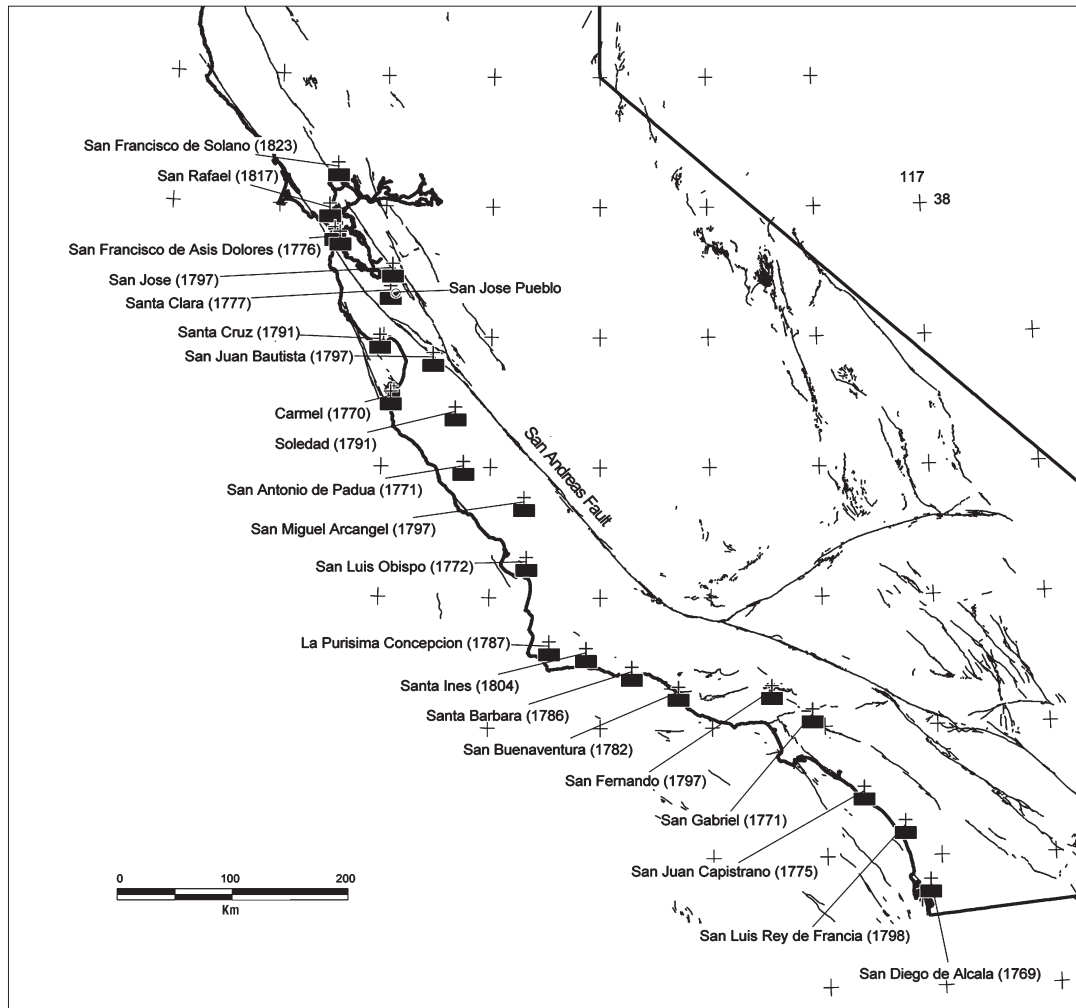


Fig. 1. Index map showing the California Missions and the dates the missions were established. All missions were secularized in 1834 (modified from Toppozada *et al.*, 2002).

of shaking intensities, and ultimately earthquake epicenters and magnitudes (table I).

The routine seismographic determinations of earthquake epicenters and magnitudes (M) started in southern California in 1932. By comparing the shaking intensities of the modern instrumentally determined earthquakes to those of pre-1932 events, the epicenters and magni-

tudes of the pre-instrumental earthquakes could be estimated with some consistency.

The short earthquake history has shown that most regions in California are susceptible at various levels to earthquake damage. This information has been applied to earthquake hazard assessment and mitigation at critical structures such as nuclear power

Table I. Significant California earthquakes ($M \sim 6$ to 6.5 and/or destructive).

Date (°)	Latitude	Longitude	M	Region	Loss of life and property
1812.12.08	34.37 (?)	-117.65 (?)	~ 7.3	Orange County, Los Angeles, Wrightwood	40 deaths at San Juan Capistrano
1812.12.21(**)	34.75 (?)	-118.60 (?)	~ 7.1	Los Angeles, Ventura, Santa Barbara	1 death
1838.06.00	37.30 (?)	-122.15 (?)	~ 7.4	San Francisco to San Juan Bautista	Damage from San Francisco to Monterey
1857.01.09	36.20	-120.80	7.9	Great Fort Tejon earthquake	1 death, damage from Monterey Co. to San Bernardino Co.
1865.10.08	37.20	-121.90	6.5	Santa Cruz Mountains	\$500 000 in property loss
1868.10.21	37.70	-122.10	7.0	Hayward Fault	30 deaths, \$350 000 loss
1872.03.26	36.70	-118.10	7.4	Owens Valley	27 deaths, 56 injuries, \$250 000 loss
1873.11.23	42.00 (?)	-124.20 (?)	6.9	Crescent City regoin	Damage in California - Oregon border area
1890.02.09	33.40	-116.30	6.8	San Jacinto fault?	Little damage
1892.02.24	32.55	-115.65	7.3	Laguna Salada, Baja California	Damage San Diego to Imperial Valley
1892.04.19	38.40	-122.00	6.6	Vacaville	1 death, \$225 000 loss
1898.03.31	38.20	-122.50	6.4	Mare Island	\$350 000 loss
1898.04.15	39.20	-123.80	~ 6.7	Fort Bragg - Mendocino	Damage from Fort Bragg to Mendocino
1899.12.25	33.80	-117.00	6.7	San Jacinto and Hemet	6 deaths, \$50 000 loss
1906.04.18	37.70	-122.50	7.8	Great 1906 earthquake	3 000 deaths, \$524 million loss (counting fire damage)
1918.04.21	33.75	-117.00	6.8	San Jacinto	1 death, several injuries, \$200 000 loss
1923.01.22	40.40	-124.90	7.2	Off Cape Mendocino	Destructive in Humboldt Co., strongly felt to Reno
1925.06.29	34.30	-119.80	6.8	Santa Barbara	13 deaths, \$8 million loss
1927.11.04	34.60	-120.90	7.1	40 km west of Lompoc	Damage in Santa Barbara and San Luis Obispo counties
1933.03.11	33.70	-118.00	6.4	Long Beach	115 deaths, \$40 million loss
1940.05.19	32.73	-115.50	7.0	Imperial Valley	9 deaths, \$6 million loss
1952.07.21	35.00	-119.02	7.3	Kern County earthquake	12 deaths, \$60 million loss
1954.12.21	40.93	-123.78	6.6	East of Arcata	1 death, several injuries, \$2.1 million loss
1971.02.09	34.41	-118.40	6.6	San Fernando	65 deaths, 2,000 + injuries, \$505 million loss
1979.10.15	32.61	-115.32	6.5	Imperial Valley	91 injuries, \$30 million loss
1980.11.08	41.12	-124.67	7.4	West of Eureka	6 injuries, \$2 million loss
1983.05.02	36.23	-120.31	6.4	Coalinga	\$31 million loss, 1 death, 47 injuries
1984.04.24	37.31	-121.68	6.2	Morgan Hill	\$8 million loss
1987.10.01	34.07	-118.08	6.0	Whittier Narrows	8 deaths, \$358 million loss
1987.11.24	33.01	-115.85	6.6	Superstition Hills	\$3 million loss
1989.10.18	37.04	-121.88	6.9	Loma Prieta	63 deaths, 3,757 injuries, \$6 billion loss
1992.04.25	40.33	-124.23	7.2	Cape Mendocino area	356 injuries, \$48.3 million loss. Two M 6.6 aftershocks next day
1992.06.28	34.20	-116.44	7.3	Landers	1 death, 402 injuries, \$91.1 million (losses include Big Bear, M 6.5, earthquake 3 hours later)
1994.01.17	34.21	-118.54	6.7	Northridge	57 deaths, 9000 + injuries, ~\$40 billion loss
1999.10.16	34.60	-116.27	7.1	Hector Mine	Minimal injuries and damage due to sparse population

Loss from Stover and Coffman (1993).

(°) The date is given as year, month, day (Greenwich).

(**) Proposed epicenter on or near San Andreas Fault (Toppozada *et al.*, 2002).

plants, dams, schools and hospitals. The historical earthquake information is also an important component of the probabilistic seismic hazards assessments that are part of the modern building codes.

2. Earthquake catalogs in California

2.1. Before 1970

The most comprehensive catalog of historical California earthquakes available before 1970 was that of Townley and Allen (1939). This provided mostly narrative descriptions of historically reported felt earthquakes, from the 1769 Spanish exploration of California to 1928. It did not generally provide epicenter coordinates or magnitudes for the earthquakes. The sources of information were mostly Catholic Mission documents before the 1849 Gold Rush, and Newspapers and varied correspondence thereafter.

The Bulletin of the Seismological Society of America (BSSA) started publication in 1910, and has included many articles on various California earthquakes. The BSSA section titled «Seismological Notes» describes the shaking and felt effects of contemporary earthquakes, with some seismographic information generally for post-1932 events.

Since 1928, the annual publication United States Earthquakes (USE) has provided descriptions of felt effects for earthquakes in the United States, and available seismographic information, such as epicenter coordinates and magnitude. Since 1950 USE has included rough isoseismal maps of some of the most widely felt earthquakes.

Special publications were also available for numerous significant events, including the major San Andreas Fault earthquakes of 1857 (Wood, 1955) and 1906 (Lawson, 1908).

2.2. The 1970s

Hileman *et al.* (1973) published the California Institute of Technology (CIT) seismographic catalog of earthquakes from 1932 to 1972 for

Southern California, roughly south of the 36th parallel. This catalog lists instrumentally determined epicenter coordinates and magnitudes, and provides annual and multi-year epicenter maps of earthquakes of various magnitudes, generally of $M > 3$. Online updates of the CIT catalog are available at: <http://www.scec.org/scec.org/catalogsearch.html>

Bolt and Miller (1975) published the University of California, Berkeley (UCB) catalog of earthquakes from 1910 to 1972, for northern California, roughly north of the 36th parallel. Their estimates of pre-1942 earthquake location and size were approximate, and generally not determined from seismographs. These estimates were largely based on Townley and Allen's (1939) descriptive catalog, except for a few seismographic values of epicenter and magnitude (M) quoted from Gutenberg and Richter (1949) and CIT. Starting in 1942, UCB seismographic records were used to determine epicenters and M for generally $M > 3$ earthquakes. Online updates of the UCB catalog are available at: <http://quake.geo.berkeley.edu/ncedc/catalog-search.html>

Toppozada (1975) analyzed the size of the areas shaken by earthquakes in California and Western Nevada at various Modified Mercalli Intensity levels (MMI), and related them to Richter local magnitude. These relations were subsequently used in the 1970s and 1980s to estimate the magnitudes of preinstrumental earthquakes.

Toppozada *et al.* (1978) interpreted the felt effects and estimated epicenters and magnitudes for the most strongly felt California earthquakes occurring from 1900 through 1931. They based their estimates on the felt effects and size of areas shaken at various levels of intensity as reported by Townley and Allen (1939) and USE. Supplemental information came from felt shaking effects described in pre-1932 newspapers, BSSA, and available seismographic information including the UCB Bulletin of the Seismographic Stations. They selected 517 events of probable $M \sim 4$ or larger based on Toppozada's 1975 relations, having Modified Mercalli Intensity (MMI) of V or larger or felt area ~ 7000 square km or larger. They determined that at least 229 earthquakes were of $M \geq 4$, but the available MMI and felt

area data were not sufficient to allow robust estimates of magnitude for the remaining events, that were probably of $M \sim 4$.

Real *et al.* (1978) combined this pre-instrumental 1900-1931 catalog with a 1932-1975 catalog that they created by merging the CIT and UCB catalogs, and the USGS catalog for Central Coastal California since 1969. Their resulting 1900-1975 catalog was available on computer tape, and on an epicenter wall map of 3600 earthquakes of $M \geq 4$ or larger, or MMI V or greater if M was unknown. The catalog lists the event dates, epicenter coordinates, and M , and includes 452 events of $M \geq 5$. This catalog is essentially pre-instrumental before 1932 in Southern California, and before 1942 in Northern California.

2.3. The 1980s

Toppozada *et al.* (1981) analyzed in detail the felt effects of the most strongly felt California

earthquakes between 1769 and 1900. They selected earthquakes from Townley and Allen (1939) of probable $M \sim 5$ or larger based on Toppozada's 1975 relations, having MMI at least VI or felt area at least 30 000 square km. They constructed isoseismal maps for 100 earthquakes, showing the reporting points and their MMI values. They supplemented the published intensity information by researching the reports of Spanish Missionaries from 1769 to 1840, mainly in the Santa Barbara Mission archives. After the advent of regular newspaper publishing with the 1849 Gold Rush, reports of feeling earthquakes became available beyond the coastal zone where the Missions were located (fig. 1), and extended inland to the goldfields East of Sacramento (fig. 2a). The newspaper coverage gradually expanded to cover most of California by the 1880s (fig. 2b).

Pre-1932 earthquakes were best known in the areas that had Catholic Missions before the 1840s, and newspaper coverage after 1849. The State epicenter map (fig. 3) employs three symbol shapes, Xs, circles and triangles, to identify



Fig. 2a. Locations of newspapers in print, 1850-1859 (modified from Toppozada *et al.*, 1981).

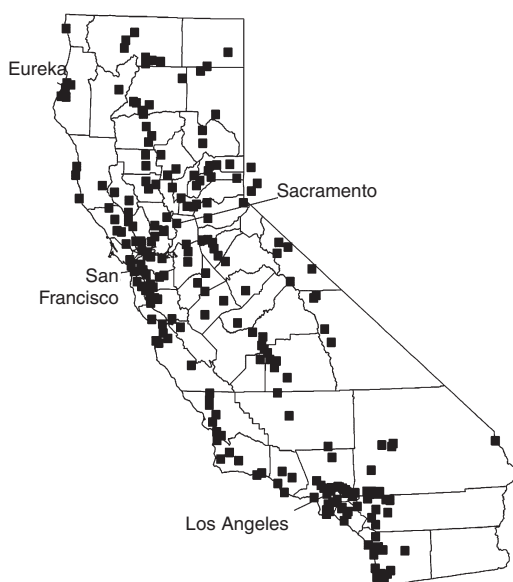


Fig. 2b. Locations of newspapers in print, 1880-1889 (modified from Toppozada *et al.*, 1981).

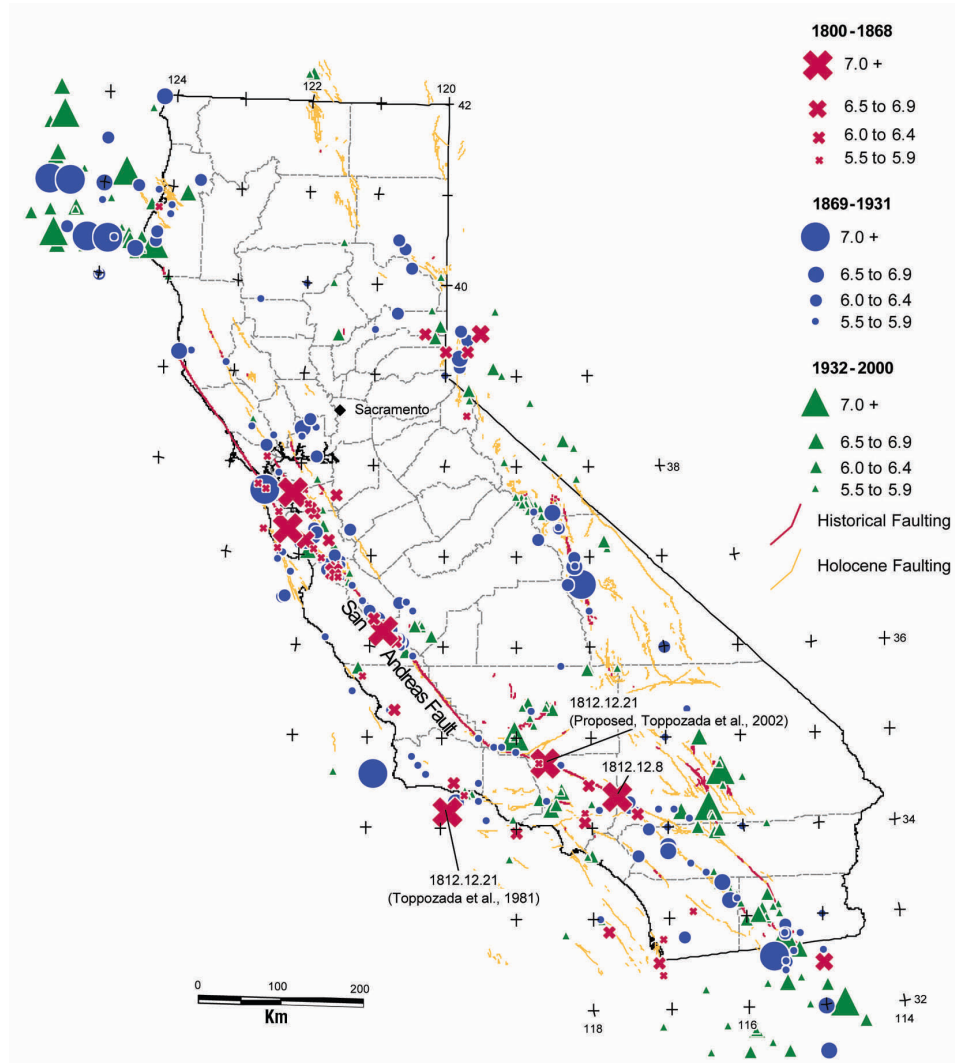


Fig. 3. Magnitude greater or equal to 5.5 California earthquakes, 1800-2000 (modified from Toppozada and Branum, 2002).

the three approximate thirds of the 200-year record. It shows that before 1869, earthquakes indicated by Xs were relatively well known in the central and southern coast and in the gold and silver fields northeast of Sacramento, but not in the northwestern or southeastern regions of California. After 1868 when the newspaper coverage expanded to these remote regions

their high seismicity became apparent, as indicated in fig. 3 by the circles and triangles in these areas. The San Andreas Fault region between the 36th and 37th parallels was much more active before than after 1932, as illustrated by the Xs and circles greatly outnumbering the triangles in this region (fig. 3). This will be discussed below under the «Parkfield region».

Most of Toppozada *et al.* (1981)'s data resulted from searching about 12 000 newspaper issues for towns that might have felt the earthquakes, for several issues after each event. About a quarter of the issues searched provided some earthquake descriptions, although many descriptions were duplicated in various newspapers. A bibliography of the newspapers searched for each earthquake was appended to the 1981 report. Also, a summary of the reported felt effects for each earthquake and the corresponding MMI value at each reporting town was appended to the 1981 report.

Toppozada and Parke (1982) completed a similar study of the areas damaged by California earthquakes that caused MMI VI to VII or greater effects in California, from 1900 to 1949. This study provided isoseismal maps and summaries of reported effects, which were not available in USE (1928-1949) or in Toppozada *et al.* (1978)'s study of pre-1932 events. A newspaper bibliography and a summary of the reported effects were also appended to the 1982 report.

2.4. 1990 to 2003

Ellsworth (1990) reviewed the history of major California and Nevada earthquakes from 1769 to 1989, and compiled a comprehensive catalog of $M \geq 6$ earthquakes. This included the known values of the various magnitude types for each earthquake, derived from MMI, short and long period seismic records, seismic moment, and a summary or preferred M .

Stover and Coffman (1993) summarized the information from USE, Toppozada *et al.* (1981), and other available sources, and provided a catalog and felt descriptions for historical earthquakes of $M \geq 4.5$. They also provided isoseismal maps for some of the most significant California events, generally of $M \geq 6.5$.

Toppozada *et al.* (2000) compiled a wall map of epicenters of $M \geq 5$ earthquakes from 1800 to 1999. This map lists the date, co-ordinates, and magnitude of the 383 events of $M \geq 5.5$. An inset map shows the areas damaged at MMI VII or greater by these earthquakes, which is the threshold of damage to weak buildings, and the number of times the various areas have been damaged.

Certain areas in the regions of Los Angeles, San Francisco, and Eureka were shaken repeatedly at MMI VII or greater at least six times each since ~1800. A generalized subset of this wall map is available on the web at: <http://www.consrv.ca.gov/cgs/rghm/quakes/MS49.htm>

Toppozada and Branum (2002) summarized the information on the $M \geq 5.5$ historical earthquakes, and the areas that they damaged. For each earthquake they listed all known values of M , and identified a preferred M . They obtained instrumental magnitudes generally for post-1932 events from the earthquake catalogs of CIT and UCB, Ellsworth (1990) for $M \geq 6.0$ events, Hutton and Jones (1993), Stein and Hanks (1998), and Bakun (1999, 2000). The preferred magnitude was moment M when available. Otherwise, the order of preference was generally M_g -r (Gutenberg and Richter, from 20-sec surface waves); M_s (from surface waves, before 1935 generally from un-damped Milne seismographs according to Abe, 1988); M_L (local M of Richter, 1935); M_a (based on the size of the areas shaken at or above MMI V, VI, VII); M_i (from Bakun 1999, 2000, using Toppozada *et al.*, 1981, MMI data). They also showed the spatial and temporal evolution of the seismicity and the areas damaged at MMI VII or greater from 1800 to 2000.

2.4.1. Updated relations between areas shaken and M

Toppozada and Branum (2002) developed new relations between the moment magnitude of modern California earthquakes of M 5.5 to 7.3 and the areas in square km that they shook at or greater than MMI V, VI, or VII (fig. 4). The standard deviations of the three linear least squares fits range from 0.11 magnitude units for M derived from MMI3V, to 0.17 for M derived from MMI3VII:

$$M_V = 0.83 \text{Log}_{10} \text{Area}_V + 2.43$$

$$\text{St. Dev.} = 0.11$$

$$M_{VI} = 0.73 \text{Log}_{10} \text{Area}_{VI} + 3.44$$

$$\text{St. Dev.} = 0.13$$

$$M_{VII} = 0.67 \text{Log}_{10} \text{Area}_{VII} + 4.29$$

$$\text{St. Dev.} = 0.17$$

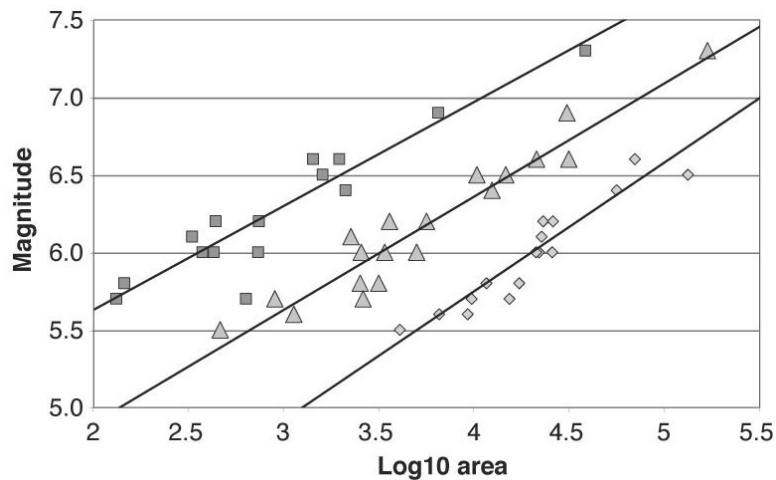


Fig. 4. Moment magnitude as a function of the areas, in km^2 , shaken at or greater than MMI V, VI, VII (modified from Toppozada and Branum, 2002).

Toppozada and Branum (2002) and Toppozada *et al.* (2002) used these relations to derive estimates of magnitude of pre-instrumental earthquakes from the areas shaken at these intensities or greater. For example the area shaken at MMI V or greater by the 12 April 1885 earthquake is that enclosed by the innermost two contours in fig. 5. That is the whole area from Visalia to Santa Cruz (E to W) and from Oakdale to Santa Maria (N to S). The values of MMI are determined at the points that described the shaking effects, and the contours are drawn to distinguish between areas having different values of MMI.

The new equations result in magnitudes that are approximately 0.3 to 0.4 units higher than those resulting from Toppozada (1975)'s relations, which were based on local magnitude values and partly on Nevada earthquakes. Ellsworth (1990) independently found that Toppozada (1975)'s relations underestimated M by about 0.2 to 0.3 units for modern California earthquakes. The 2002 relations are superior to the 1975 relations because: i) they are based on California earthquakes only whereas the 1975 relations included data from several Nevada events; ii) they are based on modern events up to the year 2000 whereas the 1975 relations included

no data after 1971; and iii) they are based on moment M whereas the 1975 relations were based on local M .

2.4.2. Selected regions

The earthquake history of selected regions of California has also been studied. For example, Agnew (1991) studied the completeness of the historical earthquake record in Southern California, in light of the distribution of newspapers and other available sources of information.

Bakun (1999, 2000) studied the seismicity of the San Francisco Bay region, and of California's North Coast, using the method of Bakun and Wentworth (1997) to determine epicenters and magnitudes for pre-instrumental earthquakes.

Uhrhammer (2003) is currently studying the early seismographic record (1910-1950) in the San Francisco Bay region, using the UCB seismic records and notebooks to revise the early epicenter and M determinations. This should distinctly improve the earthquake record before 1942 when UCB started to routinely determine epicenters and magnitudes using seismic records.

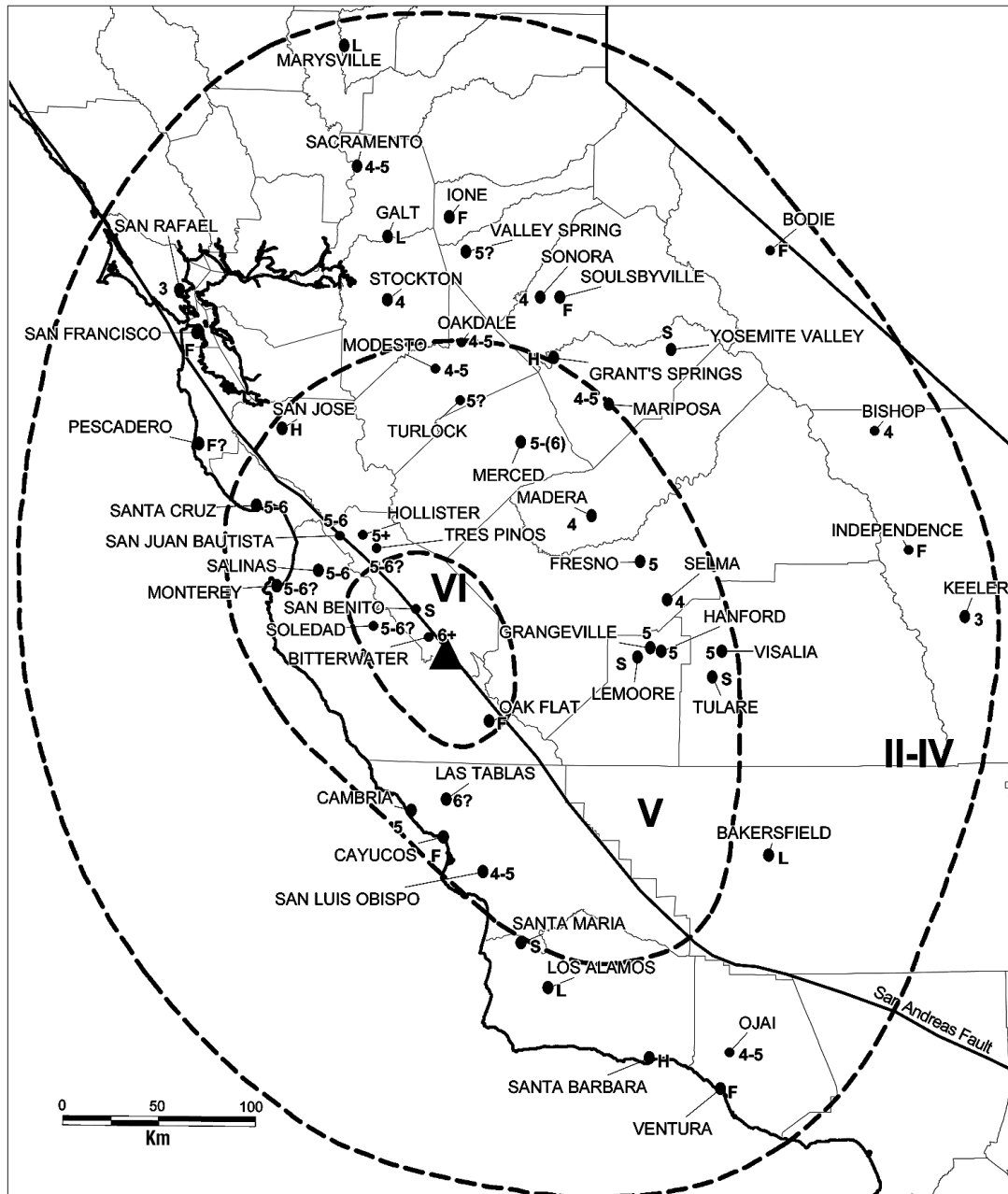


Fig. 5. 12 April 1885 isoseismal map. Numbers at towns are the MMI values based on the felt effects. When felt effects did not indicate a MMI value we use a letter: F, felt; S, severe; L, light; H, heavy. The triangle represents the epicenter. The three dashed lines represent the areas of MMI greater than or equal to II-IV, V or VI used in the magnitude-area relations of Toppozada and Brannan (2002) (modified from Toppozada *et al.*, 2002).

3. Significant results

3.1. Parkfield region

The Parkfield Earthquake prediction by Bakun and Lindh (1985) followed, and was based largely on the historical earthquake catalog work available at that time. The prediction was based on the observation that $M \sim 6$ events had occurred *quasi*-regularly near Parkfield in 1857 (identified by Sieh, 1978), 1881 (identified by Toppozada *et al.*, 1981), 1901, 1922, 1934, and 1966 (Bakun and McEvilly, 1979, 1984). This simple model predicted that the next $M \sim 6$ earthquake would occur before 1993. The predicted earthquake has not yet occurred as of this writing (September 2003).

Toppozada *et al.* (2002) undertook a detailed study of the earthquake history of the Parkfield region and adjoining segment of the San Andreas fault, based on exhaustive research of newspapers and local diaries. This study showed that the pre-1932 seismicity of Parkfield and the adjoining segment of the San Andreas fault to the north was much greater than previously thought, and has been decreasing steadily from 1857 to the present time. The simple 1985 model of Bakun and Lindh does not include the high pre-1900 San Andreas Fault seismicity within 70 km NW of Parkfield. This seismicity brackets the northern end of the major 1857 San Andreas fault rupture, which is at the largest 1857 epicenter symbol (X) in fig. 6a.

Epicenters of the strong 1885 earthquake of $M \sim 6.5$ (fig. 5) and other pre-1932 $M \sim 6$ earthquakes in this zone are shown in fig. 6a. The epicenters were estimated at the centers of strongest MMI. Relative locations of neighboring earthquakes were determined by comparing their MMI values at the same towns (*e.g.*, Parkfield, Salinas, etc.). The earthquakes in fig. 6a have isoseismal maps or descriptions of MMI in Toppozada *et al.* (2002). Their rate of occurrence indicates a decaying earthquake sequence (fig. 6b). This suggests post-earthquake stress decay at the northern end of the 1857 fault rupture, and helps explain the delay of the predicted earthquake. Figures 6a and 6b show that $M \geq 5.5$ earthquakes have occurred in the San

Andreas fault zone within 70 km northwest of Parkfield ten times from 1857 to 1932, but only twice after 1932.

Ben-Zion *et al.* (1993) modeled a decreasing stress at the terminus of the 1857 rupture that is generally compatible with that indicated by our observed decrease in earthquake rate. They concluded that the decreasing stress could delay the predicted Parkfield earthquake from ~ 1988 to ~ 1995 .

3.2. December 1812 Southern California earthquakes

Toppozada *et al.* (2002) re-evaluated the major earthquakes that occurred on 8 and 21 December 1812, damaging the Missions from San Juan Capistrano to Purisima Concepcion (fig. 7), in Orange, Los Angeles, Ventura and Santa Barbara counties. They found that the 1812 San Andreas faulting indicated by Jacoby *et al.* (1988), extending ~ 170 km from near Cajon Pass to near Fort Tejon, could have ruptured in two events and generated both earthquakes (fig. 7). Tree ring studies by Jacoby *et al.* (1988) placed the first event that damaged mostly San Juan Capistrano and San Gabriel, on the Wrightwood segment that includes Cajon Pass and Pallett Creek. Toppozada *et al.* (2002) concluded that the second faulting event 13 days later could have started from the west end of the first, with rupture directed to the west toward Fort Tejon and Purisima Concepcion. It damaged mostly Santa Barbara, Santa Inez and Purisima. Missions San Fernando and San Buenaventura were damaged by both the 8 and 21 December 1812 earthquakes (fig. 7).

The damage at Purisima Concepcion was stronger than that at Santa Inez. This was apparently due to Mission Purisima's location on sloping ground at the edge of a marsh (Toppozada *et al.*, 1981). Also, Rancho de San Antonio, 17 km north of Purisima, was not damaged (fig. 7). The adverse site effects at Mission Purisima were recognized by the padres and noted in their 1813 written communications. They consequently rebuilt Mission Purisima on flat dry ground, 5 km north of the 1812 ruins.

If the 1812 faulting extends westward to Fort Tejon, or beyond to Mil Potrero as suggested by

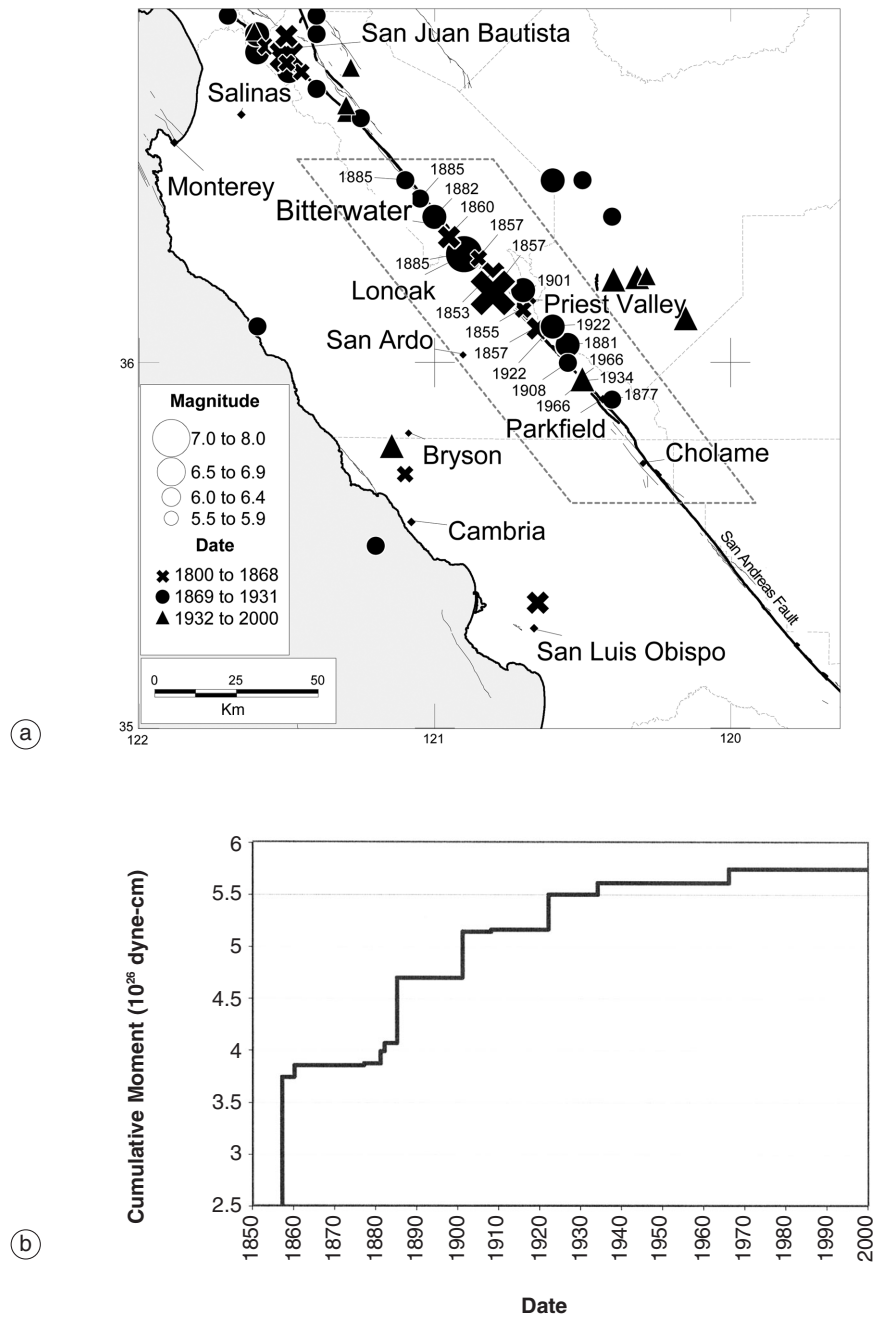


Fig. 6a,b. a) Epicenters of $M \geq 5.5$ earthquakes in the Parkfield-Bitterwater region and surrounding areas. Symbol size is proportional to M and shape indicates time period. The dashed region is that considered in fig. 6b (Modified from Toppozada *et al.*, 2002). b) Cumulative seismic moment released in the Parkfield-Bitterwater zone of the San Andreas fault from 1857 to 2001 (Modified from Toppozada *et al.*, 2002).

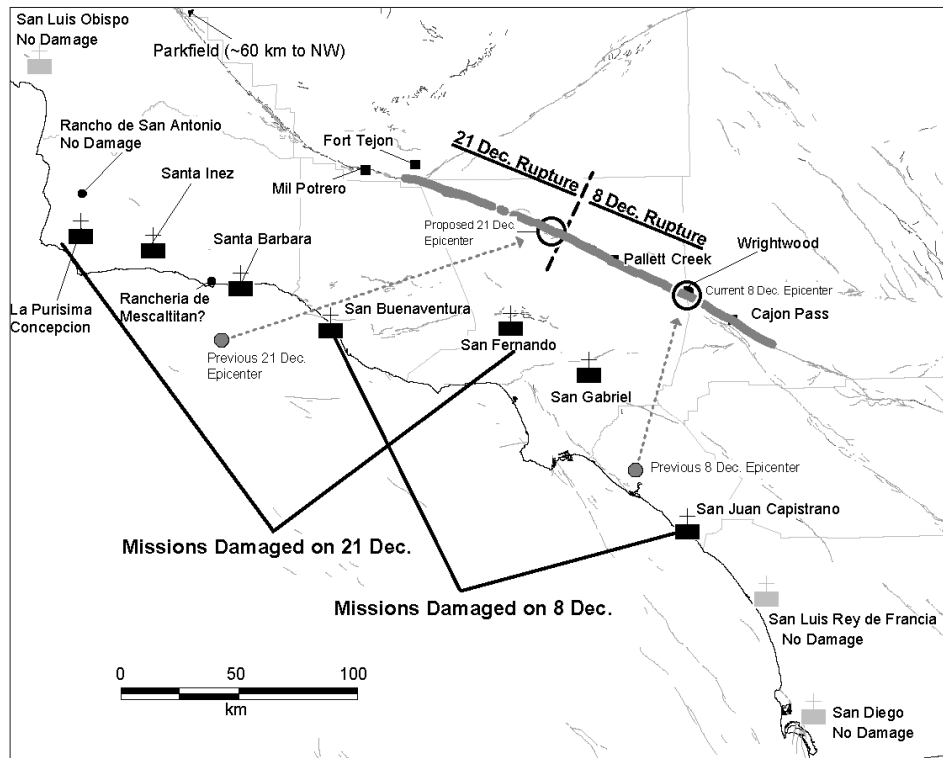


Fig. 7. Missions damaged by the December 1812 earthquakes. We divide the 1812 rupture proposed by Jacoby *et al.* (1988) into 2 segments to account for the damage observed on 8 and 21 December, and on both dates (modified from Toppozada *et al.*, 2002).

Davis (1983), it cannot all have ruptured on 8 December. Faulting that extends that far westward would damage Santa Barbara, which was not damaged on December 8th but on the 21st. Thus the total 1812 faulting suggested by Jacoby *et al.* (1988) and depicted in fig. 7 would suggest that the western segment ruptured on the 21st. Definition of the western extent of the total 1812 faulting is complicated by the major 1857 earthquake rupture that extended from near Parkfield to Cajon Pass, and re-ruptured the 1812 faulting after only 44 years.

The conventional Santa Barbara Channel epicenter of the 21 December earthquake was based largely on a tsunami that resulted from the event. However, it is becoming clear that tsunamis are often generated by submarine landslides. Lander

et al. (1993) interpreted the description of the 1812 sea wave as «a submarine landslide-generated wave and not one generated by a (submarine) fault movement source». Such landslides are mapped frequently in the Santa Barbara Channel (Greene and Kennedy, 1989), and could have been triggered by the 1812 earthquake shaking (Greene *et al.*, 2000).

3.3. 1830s San Francisco Bay area earthquakes

The destructive 1989 Loma Prieta earthquake provided the impetus for Toppozada *et al.* (1996) to study the San Francisco bay area earthquake history in detail. This led to a bet-

ter understanding of the major 1838 San Andreas fault event and to a radical re-evaluation of the 1836 «Hayward Fault earthquake» by Topozada and Borchardt (1998).

They concluded that the 1838 earthquake was of $M \sim 7.4$, significantly larger than previously thought. The 1906 San Francisco earthquake of $M 7.8$ occurred 68 years later as a result of major San Andreas faulting that overlapped and reruptured the 1838 faulting. This pair of events is similar to the 1857 Central San Andreas Fault earthquake of $M 7.9$ whose major faulting overlapped and reruptured the faulting associated with the 1812 earthquakes of $M \sim 7.3$ and ~ 7.1 .

Thus the 1857 and 1906 $M 7.8$ and 7.9 San Andreas faulting events have each overlapped a $M \sim 7.4$ faulting event that occurred 44 to 68 years earlier. Earthquake ruptures that occur 44 to 68 years apart are difficult to differentiate in fault trenches because of the limitations in stratigraphic resolution and paleoseismic dating. This suggests that overlapping ruptures occurring a few decades apart can be more common than paleoseismology would indicate.

Topozada and Borchardt (1998) also found that the 1836 event was not a $M \sim 7$ event on the Hayward fault as was previously believed, but rather a $M \sim 6 \frac{1}{2}$ event ~ 100 km to the south, in the general vicinity of Monterey Bay. The idea of an 1836 Hayward Fault earthquake had been based on successive false assumptions and misinterpretations of information, which Topozada and Borchardt summarized in their table 2: 'Evolution of the Myth concerning the 1836 «Hayward Fault earthquake»'.

4. Current work

We are building a database of the felt effects of $M > 5$ historical earthquakes. For each earthquake there are various towns that reported felt effects. The database will have a separate entry for each earthquake and each town that reported the event. We have digitized the data previously analyzed by Topozada *et al.* (1981) and Topozada and Parke (1982). We will supplement this with unpublished data that we have analyzed, and also add information for post-

1950 events from USE. The database will be searchable for event dates, towns, geographic regions, and levels of MMI shaking.

This will allow us to determine how many times specific towns, as well as regional areas, have felt different levels of MMI shaking. The database will be linked to digital isoseismal maps of the corresponding earthquakes. These maps and data will be published on a website to allow comparing the felt effects of current earthquakes to those of neighboring historical events. This will permit a rapid assessment of the potential MMI shaking and damage from a current strong earthquake from the shaking of neighboring historical events of similar magnitude. It will also allow recalibrating the epicenters and magnitudes of preinstrumental earthquakes by comparing their intensities of shaking to those of nearby well-instrumented modern earthquakes.

REFERENCES

- ABE, K. (1988): Magnitudes and origin times from Milne seismograph data: earthquakes in China and California, 1898-1912, in *Historical Seismograms and Earthquakes of the World*, edited by W.H.K. LEE, H. MEYERS and K. SHIMAZAKI (Acad. Press, San Diego, CA, U.S.A.), 37-50.
- AGNEW, D.C. (1991): How complete is the pre-instrumental record of earthquakes in Southern California, in *Environmental Perils - San Diego Region*, edited by P.L. ABBOTT and W.J. ELLIOTT (Association of Geologists, San Diego).
- BAKUN, W.H. (1999): Seismic activity of the San Francisco Bay region., *Bull. Seismol. Soc. Am.*, **89**, 764-784.
- BAKUN, W.H. (2000): Seismicity of California's North Coast, *Bull. Seismol. Soc. Am.*, **90**, 797-812.
- BAKUN, W.H. and T.V. McEVILLY (1979) Earthquakes near Parkfield, (California): comparing the 1934 and 1966 sequences, *Science*, **205**, 1375-1377.
- BAKUN, W.H. and T.V. McEVILLY (1984): Recurrence models and the Parkfield, California, earthquakes, *J. Geophys. Res.*, **89**, 3051-3058.
- BAKUN, W.H. and A.G. LINDH (1985): The Parkfield California earthquake prediction experiment, *Science*, **229** (4714), 619-624.
- BAKUN, W.H. and C.M. WENTWORTH (1997): Estimating earthquake location and magnitude from seismic intensity data, *Bull. Seismol. Soc. Am.*, **87**, 1502-1521.
- BEN-ZION, Y., J. RICE and R. DMOWSKA (1993): Interaction of the San Andreas fault creeping segment with adjacent great rupture zones and earthquake recurrences at Parkfield, *J. Geophys. Res.*, **98**, 2135-2144.
- BOLT, B.A. and R.D. MILLER, (1975): *Catalogue of earthquakes in northern California and adjoining areas, 1*

- January 1910 - 31 December 1972, *Seismographic Stations* (University of California, Berkeley, California), p. 567.
- CIT (California Institute of Technology), Southern California Seismographic Network, *Weekly Earthquake Report for Southern California*.
- DAVIS, T. (1983): Late Cenozoic structure and tectonic history of the Western «Big Bend» of the San Andreas Fault and adjacent San Emigdio Mountains, *Ph.D. Dissertation* (University of California, Santa Barbara), pp. 580.
- ELLSWORTH, W. L. (1990): Earthquake history, 1769-1989, in *The San Andreas Fault System, California, U.S. Geol. Surv. Profess. Pap. 1515*, edited by R. WALLACE (US Government Printing Office, Washington, DC), 153-188.
- GREENE, H.G. and M.P. KENNEDY (Editors) (1989): *Central California Continental Margin - Map5A*, California Division of Mines and Geology.
- GREENE, H.G., N. MAHER and C.K. PAULL (2000): Landslide Hazards off of Santa Barbara, California, in *American Geophysical Union Fall Meeting Program*, p. 291.
- GUTENBERG, B., and C. F. RICHTER (1949): *Seismicity on the Earth and Associated Phenomena* (Princeton University Press, Princeton, New Jersey), p. 273.
- HILEMAN, J.A., C.R. ALLEN and J.M. NORDQUIST (1973): Seismicity of the Southern California Region, 1 January 1932 to 21 December 1972, *Seismol. Lab. Contrib. 2385* (Calif. Institute of Technology, Pasadena), pp. 81.
- HUTTON, L.K. and L.M. JONES (1993): Local magnitudes and apparent variations in seismicity rates in Southern California, *Bull. Seismol. Soc. Am.*, **83**, 313-329.
- JACOBY, G., P. SHEPPARD and K. SEIH (1988): Irregular recurrence of large earthquakes along the San Andreas Fault - evidence from trees, *Science*, **241**, 196-199.
- LANDER, J. F., P. A. LOCKRIDGE and M.J. KOZUCH (1993): Tsunamis affecting the west coast of the United States 1806-1992, *NGDC Key to Geophysical Records Doc. 29* (US Dept. of Commerce), p. 242.
- LAWSON, A.C. (1908): *The California earthquake of April 18, 1906* (Carnegie Institute, Washington, DC).
- REAL, C.R., T.R. TOPPOZADA and D. L. PARKE (1978): Earthquake epicenter map of California, *Div. Mines Geol. Map Sheet No. 39*.
- RICHTER, C.F. (1935): An instrumental earthquake magnitude scale, *Bull. Seismol. Soc. Am.*, **25**, 1-32.
- SIEH, K.E. (1978): Central California foreshocks of the great 1857 earthquake, *Bull. Seismol. Soc. Am.*, **68**, 1731-1749.
- STEIN, R. S. and T. C. HANKS (1998): $M \geq 6$ earthquakes in southern California during the twentieth century: no evidence for a seismicity or moment deficit, *Bull. Seismol. Soc. Am.*, **88**, 635-652.
- STOVER, C. W. and J.L. COFFMAN (1993): Seismicity of the United States, 1568-1989, *U.S. Geol. Surv. Prof. Pap. 1527*, pp. 418 (revised).
- TOPPOZADA, T.R. (1975): Earthquake magnitude as a function of intensity data in California and Western (Nevada), *Bull. Seismol. Soc. Am.*, **65**, 1223-1238.
- TOPPOZADA, T.R., D.L. PARKE and C. T. HIGGINS (1978): Seismicity of California 1900-1931, *Cal. Div. Mines. Geol. Spec. Rep. 135*.
- TOPPOZADA, T.R., C.R. REAL and D.L. PARKE (1981): Preparation of isoseismal maps and summaries of reported effects for pre-1900 California earthquakes, *Calif. Div. Mines Geol. Open-File Rep. 81-11 SAC*, pp. 182.
- TOPPOZADA, T.R. and D.L. PARKE (1982): Areas damaged by California earthquakes, 1900-1949, *Calif. Div. Mines Geol. Open-File Rep. 82-17*, pp. 65.
- TOPPOZADA, T.R., G. BORCHARDT, C.L. HALLSTROM, and D. RANSOM (1996): Using 1800's earthquake sequences to elucidate the increased San Francisco Bay area seismicity since 1979, *Annual Technical Report to USGS/NEHRP*, pp. 32.
- TOPPOZADA, T.R. and G. BORCHARDT (1998): Re-evaluation of the 1836 Hayward and the 1838 San Andreas Fault earthquakes, *Bull. Seismol. Soc. Am.*, **88**, 140-159.
- TOPPOZADA, T. R., D. BRANUM, M. PETERSEN, C. HALLSTROM, C. CRAMER and M. REICHLER (2000): Epicenters of and areas damaged by $M \geq 5$ California earthquakes, 1800-1999, *Calif. Div. Mines Geol. Map Sheet 49*.
- TOPPOZADA, T.R. and D. BRANUM (2002): California $M \geq 5.5$ earthquakes, history and areas damaged, in *International Handbook of Earthquake and Engineering Seismology*, edited by W.H. LEE, H. KANAMORI and P. JENNINGS (International Association of Seismology and Physics of the Earth's Interior).
- TOPPOZADA, T.R., D.M. BRANUM, M. S. REICHLER and C. L. HALLSTROM (2002): San Andreas Fault zone, California: $M \geq 5.5$ earthquake history, *Bull. Seismol. Soc. Am.*, **92**, 2555-2601.
- TOWNLEY, M.D. and M.W. ALLEN (1939): Descriptive catalog of earthquakes of the Pacific coast of the United States, 1769 to 1928, *Bull. Seismol. Soc. Am.*, **29**, 1-297.
- UHRHAMMER, R.A. (2003): Historical earthquake reanalysis project: San Francisco Bay region, *Seismol. Res. Lett.*, **74** (2), p. 217.
- UCB (1910-1931): *Bulletin of the Seismographic Stations (BSSUC)*, *Semi-Annual Publication*, University of California at Berkeley (UCB).
- USE (1928-1985): *United States Earthquakes (USE)*, *Annual Publication*, Department of Commerce, Coast and Geodetic Survey; Department of the Interior, Geological Survey (Washington, DC).
- WOOD, H.O. (1955): The 1857 earthquake of California, *Bull. Seismol. Soc. Am.*, **45**, 47-67.